# Parity nonconservation in radiative recombination of electrons with heavy hydrogenlike ions

A.V. Maiorova,[1] O.I. Pavlova,[1] V. M. Shabaev,[1]
C. Kozhuharov,[2] G. Plunien,[3] and T. Stöhlker[2]

[1] *Department of Physics, St.Petersburg State University, Ulianovskaya 1, Petrodvorets, St.Petersburg 198504, Russia*

[2] *Gesellschaft für Schwerionenforschung, Planckstrasse 1, D-64291 Darmstadt, Germany and*

[3] *Institut für Theoretische Physik, TU Dresden, Mommsenstraße 13, D-01062 Dresden, Germany*



## Abstract

The parity nonconservation effect on the radiative recombination of electrons with heavy hydrogenlike ions is studied. Calculations are performed for the recombination into the $2^1S_0$ state of helium-like thorium and gadolinium, where, due to the near-degeneracy of the opposite-parity $2^1S_0$ and $2^3P_0$ states, the effect is strongly enhanced. Two scenarios for possible experiments are studied. In the first scenario, the electron beam is assumed to be fully polarized while the H-like ions are unpolarized and the polarization of the emitted photons is not detected. In the second scenario, the linearly polarized photons are detected in an experiment with unpolarized electrons and ions. Corresponding calculations for the recombination into the $2^3P_0$ state are presented as well.

PACS numbers: 11.30.Er, 34.80.Lx

## I. INTRODUCTION

Investigations of the parity nonconservation (PNC) effects in atoms remain an effective tool for tests of the standard model (SM) and its various extensions [1, 2, 3]. High-precision measurement of the 6$s$-7$s$ PNC amplitude in $^{133}$Cs [4, 5], combined with the recent progress on the QED and atomic-structure calculations [6, 7, 8, 9, 10, 11, 12, 13, 14, 15], provided the most accurate to-date test of the electroweak sector of the SM at the low-energy regime. From the theoretical side, one of the main difficulties in calculations of the PNC effects in neutral atoms consists in the high-precision evaluation of the electron-correlation contributions (see Ref. [15] and references therein). This problem disappears if one deals with few-electron highly charged ions, where the electron-correlation effects, being suppressed by a factor $1/Z$ ($Z$ is the nuclear charge number), can be evaluated by perturbation theory to the required accuracy.

The PNC effects in highly charged ions were first discussed by Gorshkov and Labzowsky in Refs. [16], where a proposal to use close opposite-parity levels $2^1S_0$ and $2^3P_1$ for $Z \approx 6$ and $Z \approx 29$ was made. An idea for detecting parity violation in He-like ions with $Z \approx 6$ by investigating the induced $2^3S_1$ - $2^1S_0$ transition in the presence of electric and magnetic fields was considered by von Oppen [17]. Various scenarios for observing the PNC effect in He-like uranium using the near-degeneracy of the $2^1S_0$ and $2^3P_0$ states were discussed in Refs. [18, 19, 20]. Schäfer *et al.* [18] estimated the laser intensities required to observe the PNC asymmetry in the two-photon $2^3P_0$ - $2^1S_0$ transition. Karasiev *et al.* [19] evaluated the degree of circular polarization of photons emitted in the hyperfine-quenched one-photon $2^1S_0$ - $1^1S_0$ transition. An idea to study the PNC effect on the two-photon $2^3P_0$ - $1^1S_0$ transition, stimulated by the circularly polarized optical laser, was proposed by Dunford [20]. PNC experiments with polarized ion beams at $Z \approx 64$, where the $2^1S_0$ and $2^3P_0$ states of He-like ions are also near degenerate, were suggested by Labzowsky *et al.* [21]. As in Ref. [19], here the hyperfine-induced one-photon $2^1S_0$ - $1^1S_0$ transition was considered. A detailed analysis of possibilities for the PNC experiments with heavy H-like ions was presented by Zolotarev and Budker [22]. The parity-violating effect on the Auger decay of doubly-excited states of He-like uranium was examined by Pindzola [23]. In Ref. [24], Gribakin *et al.* have studied the PNC effect on the cross section of dielectronic recombination into doubly excited states of He-like ions at $Z < 60$.

In the present paper, we study the PNC effect on the one-photon radiative recombination (RR) of an electron into the $2^1S_0$ and the $2^3P_0$ state of He-like ions nearby $Z = 90$ and $Z = 64$, where the opposite-parity states $2^1S_0$ and $2^3P_0$ are close to crossing.

Relativistic units ($\hbar = c = 1$) and the Heaviside charge unit ($\alpha = e^2/(4\pi)$, $e < 0$) are used throughout the paper.

## II. BASIC FORMULAS

Theory of the radiative recombination of electrons with highly-charged ions was considered by many authors [25, 26, 27, 28, 29, 30, 31]. In the present paper, we consider the one-photon radiative recombination of an electron having the asymptotic four-momentum $p_i = (p_i^0, \mathbf{p})$ and the spin projection $\mu_i$ with a heavy H-like ion being originally in the $1s$ ground state. Here — and in what follows — it is assumed that the momentum $\mathbf{p}_i$ is directed along the quantization axis ($z$ - axis). Since we are interested in the PNC effect, we consider that the electron is captured into the $2^1S_0$ (or, alternatively, $2^3P_0$) state of a heavy helium-like ion with $Z \approx 90$ or $Z \approx 64$, where the opposite-parity states $2^1S_0$ and $2^3P_0$ are near degenerate. This capture is accompanied by the emission of a photon with momentum $\mathbf{k}$, energy $k^0 = |\mathbf{k}| = p_i^0 - E_{2^1S_0}$, and polarization $\epsilon^\nu = (0, \boldsymbol{\epsilon})$. To zeroth order, the cross section of the process is given by [26]

$$\frac{d\sigma}{d\Omega} = \frac{(2\pi)^4}{v_i}\mathbf{k}^2 |\langle f|R^\dagger(1) + R^\dagger(2)|i\rangle|^2 \,, \tag{1}$$

where $|i\rangle$ and $|f\rangle$ denote the initial and final states of the two-electron system, $R = -e\boldsymbol{\alpha}\cdot\mathbf{A}$ is the transition operator acting on the electron variables labeled in Eq. (1) by the indices 1 and 2, respectively,

$$\mathbf{A}(\mathbf{x}) = \frac{\boldsymbol{\epsilon}\exp{(i\mathbf{k}\cdot\mathbf{x})}}{\sqrt{2k^0(2\pi)^3}} \tag{2}$$

is the wave function of the emitted photon, and $v_i$ is the initial electron velocity. Since for heavy few-electron ions the interelectronic-interaction effects are suppressed by a factor $1/Z$, compared to the electron-nucleus Coulomb interaction, we can consider the wave functions of the initial and final states in the one-electron approximation. The uncertainty due to neglecting the interelectronic-interaction and QED corrections should not exceed a few-percent level [32, 33, 34]. With this approximation, the initial state is described by the wave

function

$$u_i(\mathbf{x}_1,\mathbf{x}_2) = \frac{1}{\sqrt{2}}(\psi_{j\,m}(\mathbf{x}_1)\psi_{p_i\,\mu_i}(\mathbf{x}_2) - \psi_{j\,m}(\mathbf{x}_2)\psi_{p_i\,\mu_i}(\mathbf{x}_1))\,, \tag{3}$$

where $\psi_{j\,m}(\mathbf{x})$ is the one-electron $1s$ wave function and $\psi_{p_i\,\mu_i}(\mathbf{x})$ is the incident electron wave function. If we neglect the interelectronic and the weak electron-nucleus interaction, the wave function of the final ($2^1S_0$ or $2^3P_0$) state is given by

$$u_f(\mathbf{x}_1,\mathbf{x}_2) = \frac{1}{\sqrt{2}}\sum_{m_1,m_2} C^{00}_{j_1\,m_1,j_2\,m_2}(\psi_{j_1\,m_1}(\mathbf{x}_1)\psi_{j_2\,m_2}(\mathbf{x}_2) - \psi_{j_1\,m_1}(\mathbf{x}_2)\psi_{j_2\,m_2}(\mathbf{x}_1))\,, \tag{4}$$

where $\psi_{j_1\,m_1}(\mathbf{x})$ is the one-electron $1s$ wave function, $\psi_{j_2\,m_2}(\mathbf{x})$ is the one-electron $2s$ ($2p_{1/2}$) wave function, and $C^{JM}_{j_1\,m_1,j_2\,m_2}$ is the Clebsch-Gordan coefficient. To account for the weak interaction we must modify the wave function of the $2^1S_0$ ($2^3P_0$) state by admixing the $2^3P_0$ ($2^1S_0$) state. This yields

$$|2^1S_0\rangle \to |2^1S_0\rangle + \frac{\langle 2^3P_0|H_W(1)+H_W(2)|2^1S_0\rangle}{E_{2^1S_0}-E_{2^3P_0}}|2^3P_0\rangle\,, \tag{5}$$

$$|2^3P_0\rangle \to |2^3P_0\rangle + \frac{\langle 2^1S_0|H_W(1)+H_W(2)|2^3P_0\rangle}{E_{2^3P_0}-E_{2^1S_0}}|2^1S_0\rangle\,, \tag{6}$$

where

$$H_W = -(G_F/\sqrt{8})Q_W\rho_N(r)\gamma_5 \tag{7}$$

is the nuclear spin-independent weak-interaction Hamiltonian [1], $G_F$ is the Fermi constant, $Q_W \approx -N + Z(1-4\sin^2\theta_W)$ is the weak charge of the nucleus, $\gamma_5$ is the Dirac matrix, and $\rho_N$ is the nuclear weak-charge density normalized to unity. A simple evaluation of the weak-interaction matrix element gives

$$\begin{aligned}\langle 2^3P_0|H_W(1)+H_W(2)|2^1S_0\rangle &= \langle 2p_{1/2}|H_W|2s\rangle \\ &= i\frac{G_F}{2\sqrt{2}}Q_W\int_0^\infty dr\,r^2\rho_N(r)[g_{2p_{1/2}}f_{2s} - f_{2p_{1/2}}g_{2s}]\,.\end{aligned} \tag{8}$$

The large and small radial components of the Dirac wave function, $g(r)$ and $f(r)$, are defined by

$$\psi_{n\kappa m}(\mathbf{r}) = \begin{pmatrix} g_{n\kappa}(r)\Omega_{\kappa m}(\mathbf{n}) \\ if_{n\kappa}(r)\Omega_{-\kappa m}(\mathbf{n})\end{pmatrix}\,, \tag{9}$$

where $\kappa = (-1)^{j+l+1/2}(j+1/2)$ is the Dirac quantum number. Then formulas (5)-(6) can be written as

$$|2^1S_0\rangle \to |2^1S_0\rangle + i\xi|2^3P_0\rangle\,, \tag{10}$$

$$|2^3P_0\rangle \to |2^3P_0\rangle + i\xi|2^1S_0\rangle\,, \tag{11}$$

where

$$\xi = \frac{G_F}{2\sqrt{2}}\frac{Q_W}{E_{2^1S_0}-E_{2^3P_0}}\int_0^\infty dr\, r^2\rho_N(r)[g_{2p_{1/2}}f_{2s} - f_{2p_{1/2}}g_{2s}]\,. \tag{12}$$

With this correction, the differential cross section of recombination into the $2^1S_0$ state, $\sigma \equiv d\sigma/d\Omega$, can be written in terms of the one-electron matrix elements:

$$\sigma = \frac{1}{2}\frac{(2\pi)^4}{v_i}\mathbf{k}^2\Big\{|\langle 2s-m|R^\dagger|p_i\mu_i\rangle|^2 + 2\Re[i\xi\langle 2s-m|R^\dagger|p_i\mu_i\rangle\langle p_i\mu_i|R|2p_{1/2}-m\rangle]\Big\}\,, \tag{13}$$

where $m$ is the angular momentum projection of the initial $1s$ electron. The corresponding expression for the recombination into the $2^3P_0$ state is given by

$$\sigma = \frac{1}{2}\frac{(2\pi)^4}{v_i}\mathbf{k}^2\Big\{|\langle 2p_{1/2}-m|R^\dagger|p_i\mu_i\rangle|^2 + 2\Re[i\xi\langle 2p_{1/2}-m|R^\dagger|p_i\mu_i\rangle\langle p_i\mu_i|R|2s-m\rangle]\Big\}\,. \tag{14}$$

The incoming electron wave function is given by the partial wave expansion

$$|p_i\mu_i\rangle = \frac{1}{\sqrt{4\pi}}\frac{1}{\sqrt{p_i\varepsilon_i}}\sum_\kappa \mathrm{i}^l\exp(i\Delta_\kappa)\sqrt{2l+1}\,C^{j\mu_i}_{l0,\,\frac{1}{2}\mu_i}\;|\varepsilon_i\kappa\mu_i\rangle\;, \tag{15}$$

where $\Delta_\kappa$ is the Coulomb phase shift and $|\varepsilon_i\kappa\mu_i\rangle$ is the partial electron wave with the energy $\varepsilon_i = p_i^0$ and the Dirac quantum number $\kappa$. This expansion enables one to express the free–bound transition amplitude as a sum of partial amplitudes

$$\begin{aligned}\langle p_i\mu_i\,|R|\,n_bj_b\mu_b\rangle \;&=\; \frac{1}{\sqrt{4\pi}}\frac{1}{\sqrt{p_i\varepsilon_i}}\sum_\kappa(-\mathrm{i})^l\,\exp(-i\Delta_\kappa)\sqrt{2l+1}\\ &\times\; C^{j\mu_i}_{l0,\,\frac{1}{2}\mu_i}\;\langle\varepsilon_i\kappa\mu_i\,|R|\,n_bj_b\mu_b\rangle\;.\end{aligned} \tag{16}$$

The latter amplitude is evaluated employing the standard partial wave decomposition for the photon wave function (see, e.g., Refs. [30, 35]). The angular integrations are carried out analytically while the radial integrations are accomplished numerically. The RADIAL package [36] is used to calculate the bound and continuum wave functions for extended nuclei.

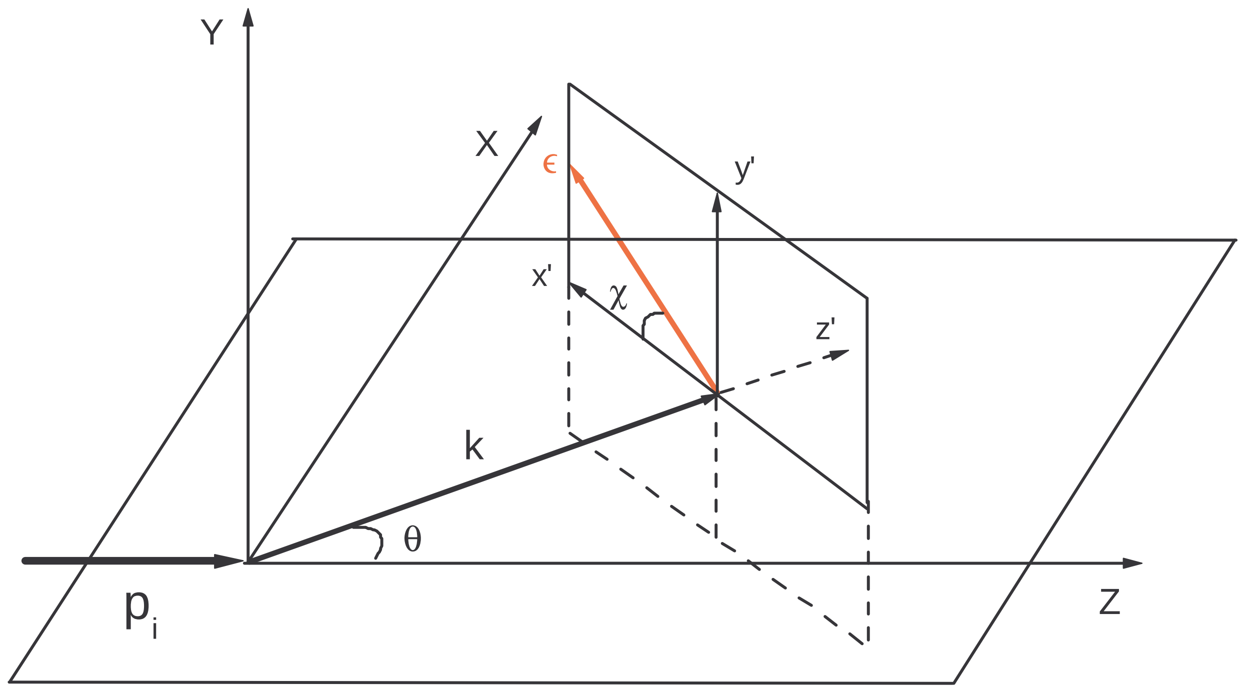


FIG. 1: Geometry (in the ion rest frame) for one-photon radiative recombination of a free electron into an excited state of a projectile ion. The unit vector of the linear polarization of the photon is defined in the plane that is perpendicular to the photon momentum.

## III. RESULTS AND DISCUSSION

The formulas (13)-(14) represent the differential cross section at given values of the bound-electron angular momentum projection $m$, the incoming electron polarization $\mu_i$, and the outgoing photon polarization $\boldsymbol{\epsilon}$. To investigate the role of the PNC effect, we consider two different scenarios for an experiment. In the first scenario, the incident electron is polarized, while the H-like ion is unpolarized, and the photon polarization is not detected. In this scenario, the cross sections (13)-(14) must be averaged over the bound-electron angular momentum projection $m$ and summed over the outgoing photon polarization $\boldsymbol{\epsilon}$. Since recent advances in polarization techniques [37, 38] make measurements of the linear polarization of x–rays feasible, as the second one we consider a scenario, in which linearly polarized photons are detected in an experiment with unpolarized electrons and ions. In this scenario, we have to avarage over $m$ and $\mu_i$, and consider the photon linearly polarized under the angle $\chi$ with respect to the reference plane that is spanned by the incident electron and the emitted photon momenta (Fig. 1).

Since we are interested in observing the PNC effects, we should search for situations where these effects are enhanced as much as possible. As indicated above, the most promising situation occurs in cases where the $2^1S_0$ and $2^3P_0$ levels almost cross. The ions with $Z \approx 90$ and $Z \approx 64$ are presently considered as the best candidates for that. In Table I, we list the theoretical predictions for the $2^3P_0$ - $2^1S_0$ energy difference in ions near the crossing points [39, 40]. Compared to Ref. [39], these data are obtained using the revised values of the nuclear charge radii for $^{238}$U and $^{232}$Th [40, 41] as well as recent results for the two-loop QED contributions [42]. As seen from the table, the maximum enhancement takes place in the cases of Th and Gd. Although the current theoretical accuracy is not high enough, one can expect that the energy differences considered can be determined to the desired accuracy in an experiment [43]. In accordance with the table, to estimate the PNC effect we use 0.44 eV and 0.074 eV for the $2^3P_0$ - $2^1S_0$ energy difference in the cases of Th and Gd, respectively. We note that in both cases the energy differences utilized are significantly larger than the corresponding natural line widths.

As the next step, one should determine the sensitivity requirements for an experimental apparatus capable for observing the PNC effect to a given accuracy. Let us consider these requirements for the first experimental scenario with a fully polarized electron beam. Denoting by $\sigma_+(\theta)$ and $\sigma_-(\theta)$ the cross sections for the positive and negative helicities (the spin projection onto the electron momentum direction) of the incident electron, we can write for the related numbers of counts

$$N_\pm = LT(\sigma_\pm + \sigma_{\rm b}) \,, \tag{17}$$

where $\sigma_{\rm b}$ is the background magnitude, $T$ is the acquisition time, and $L$ is the luminosity defined by the experimental conditions. Let us assume that we want to measure the PNC effect with a relative uncertainty $\eta$. Then, taking into account that the statistical error of $N_+ - N_-$ is given by $\sqrt{N_+ + N_-}$, one derives the following requirement for the luminosity (cf. Ref. [24])

$$L > L_0 = \frac{\sigma_+ + \sigma_- + 2\sigma_{\rm b}}{(\sigma_+ - \sigma_-)^2\eta^2 T} \,. \tag{18}$$

For the following analysis we neglect the background signal $\sigma_b$ and assume the acquisition time $T$ is equal two weeks.

We calculated $L_0$ for different inclination angles $\theta$ and different incident electron energies. Table II presents numerical results for the radiative recombination into the $2^1S_0$ and the

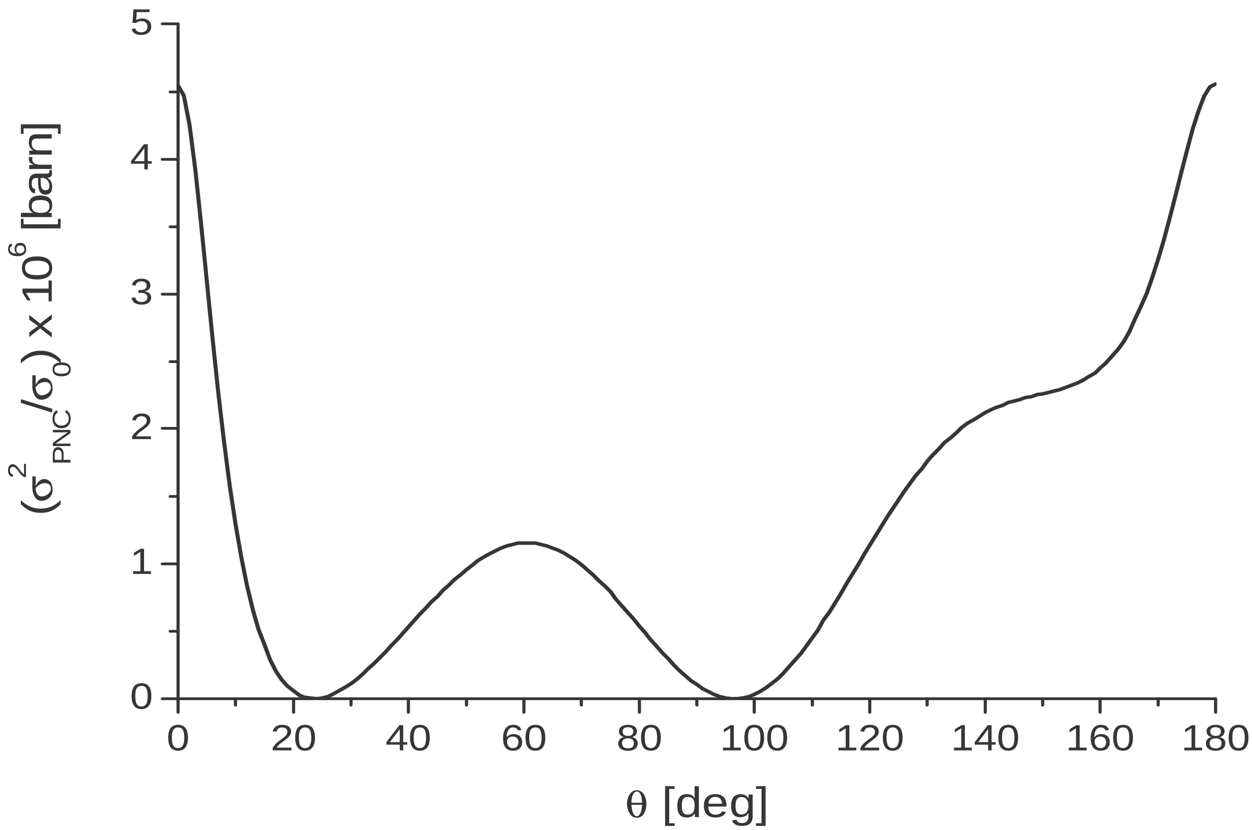


FIG. 2: The value $\sigma^2_{\rm PNC}/\sigma_0 \sim 1/L_0$ as a function of $\theta$ for the radiative recombination into the $2^1S_0$ state of He-like thorium at the incident electron energy of 1 eV. It is assumed that the incoming electron is polarized while the H-like ion is unpolarized and the photon polarization is not detected.

$2^3P_0$ state of He-like thorium at the angles $\theta$ corresponding to the minimum values of the luminosity $L_0$. For completeness, the cross section without the PNC effect, $\sigma_0 = (\sigma_+ + \sigma_-)/2$, and the PNC contribution, $\sigma_{\rm PNC} = (\sigma_+ - \sigma_-)/2$, are presented as well. In Figs. 2 and 3, we display the values $\sigma^2_{\rm PNC}/\sigma_0 \sim 1/L_0$ as functions of $\theta$ for the radiative recombination into the $2^1S_0$ and the $2^3P_0$ state, respectively, at the incident electron energy of 1 eV.

Tables III and IV present numerical results for the second scenario, where linearly polarized photons are detected in an experiment with unpolarized electrons and ions. As before, $\sigma_0$ denotes the cross section without the PNC effect and $\sigma_{\rm PNC}$ is the PNC contribution. Again, the angles $\theta$ and $\chi$ considered in Tables III and IV correspond to the minimum values of the luminosity. In this scenario, the sign of the PNC contribution $\sigma_{\rm PNC}$ is changed if the polarization angle $\chi$ is replaced by $\pi - \chi$. In Figs. 4 and 5, we display the value $\sigma^2_{\rm PNC}/\sigma_0 \sim 1/L_0$ as a function of $\theta$ and $\chi$ for the RR into the $2^1S_0$ and the $2^3P_0$ state,

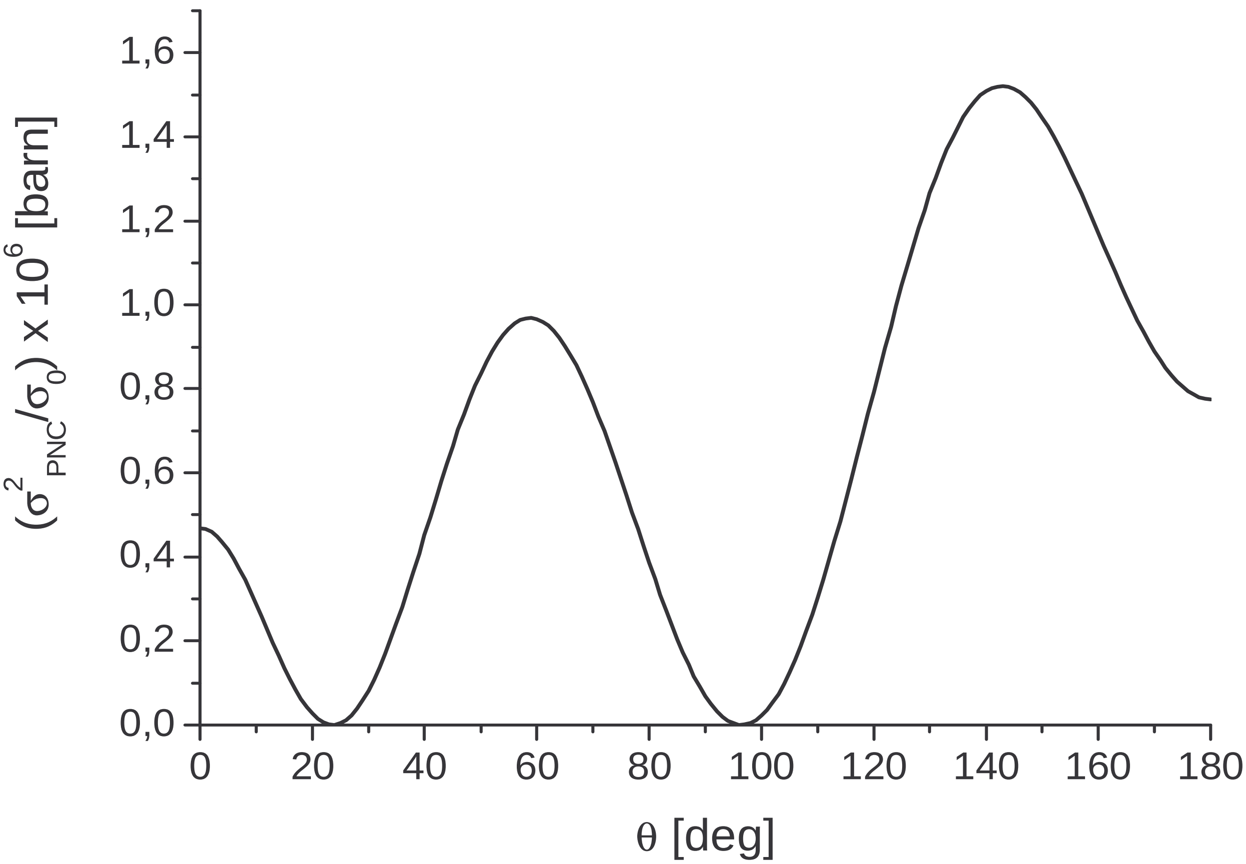


FIG. 3: The value $\sigma^2_{\rm PNC}/\sigma_0 \sim 1/L_0$ as a function of $\theta$ for the radiative recombination into the $2^3P_0$ state of He-like thorium at the incident electron energy of 1 eV. It is assumed that the incoming electron is polarized while the H-like ion is unpolarized and the photon polarization is not detected.

respectively, at the incident electron energy of 1 eV. The change of the sign of the PNC contribution $\sigma_{\rm PNC}$ under the replacement $\chi \to \pi - \chi$ means, in particular, that measuring the count rate difference between the two linear polarizations, which can be achieved in the same experiment by setting the detectors at different azimuth angles $\phi$, can provide a direct access to the pure PNC effect. With this in mind, in Table V we present numerical results for the angles $\theta$ and $\chi$ corresponding to the maximum absolute values of $\sigma_{\rm PNC}$. We note that the contribution $\sigma_{\rm PNC}$ has the same absolute values but carries opposite signs for the radiative recombination into the $2^1S_0$ and the $2^3P_0$ state, respectively. It follows that the PNC effect disappears if one measures the cross section of the RR into both $2^1S_0$ and $2^3P_0$ states. To observe the PNC effect we need to detect the photons that originate from only one of these processes: either from the RR into the $2^1S_0$ state or from the RR into the $2^3P_0$ state. Although at present the experimental resolution is far from being sufficient to detect

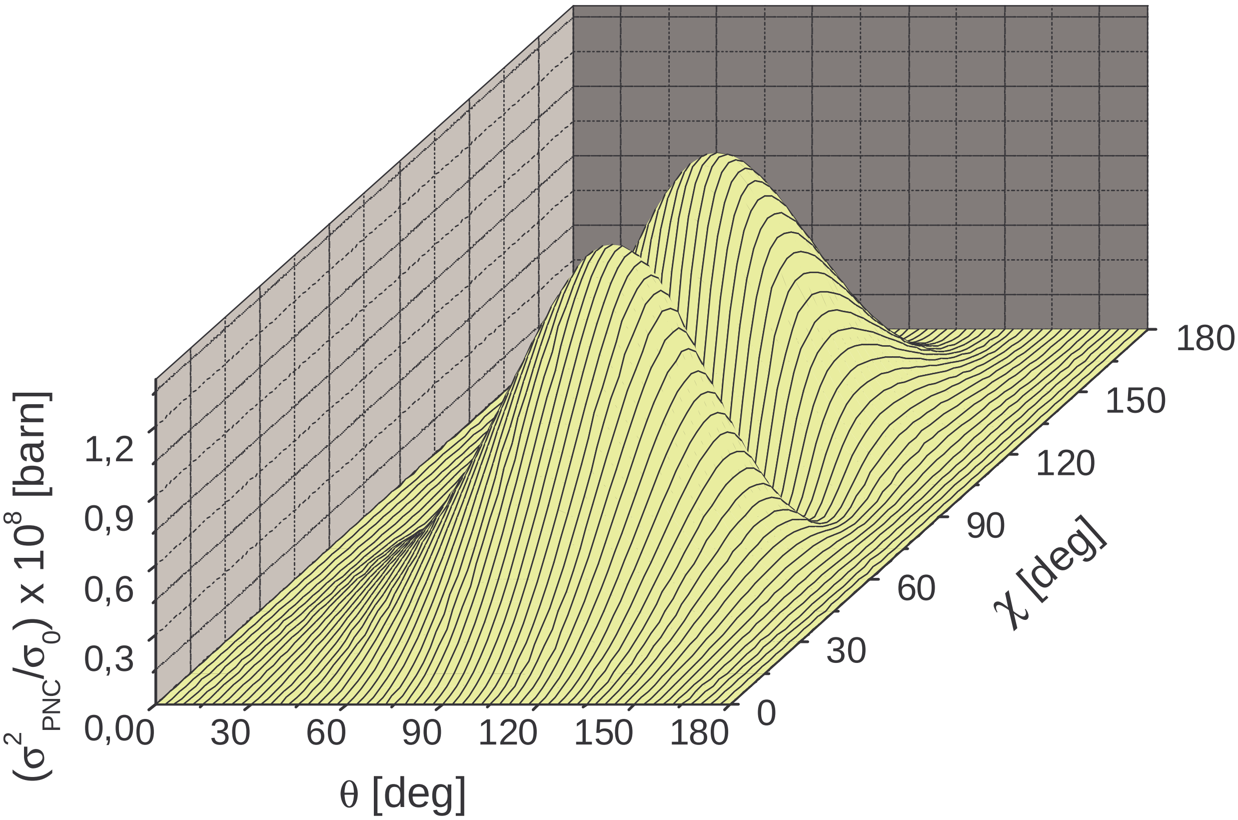


FIG. 4: The value $\sigma^2_{\rm PNC}/\sigma_0 \sim 1/L_0$ as a function of the inclination ($\theta$) and polarization ($\chi$) angles for the radiative recombination into the $2^1S_0$ state of He-like thorium at the incident electron energy of 1 eV. It is assumed that linearly polarized photons are detected in the experiment with unpolarized electrons and ions. The PNC contribution $\sigma_{\rm PNC}$ changes the sign under the replacement $\chi \to \pi - \chi$.

the desired transition line, we think that with some experimental ingenuity the blinding line could be eliminated. Alternatively, one might consider the same experiment at other values of $Z$, where the $2^3P_0$ - $2^1S_0$ energy difference becomes larger while the PNC effect remains still sizeable.

The corresponding calculations have been also performed for the $^{158}$Gd ion. It was found that, at the $2^3P_0$-$2^1S_0$ energy splitting of 0.074 eV, the PNC effect is smaller than that for thorium. In particular, in the first scenario for $p_i^0 = 1$ eV the minimum luminosity for the RR into the $2^1S_0$ state amounts to $2.5 \times 10^{28}$ cm$^{-2}$s$^{-1}$ at $\theta = 0$. The corresponding values of the cross section contributions are $\sigma_0$=287.65 barn and $\sigma_{\rm PNC} = 0.0069$ barn. In the second scenario, at the same kinetic electron energy, the minimum luminosity, $L_0 = 7.1 \times 10^{31}$

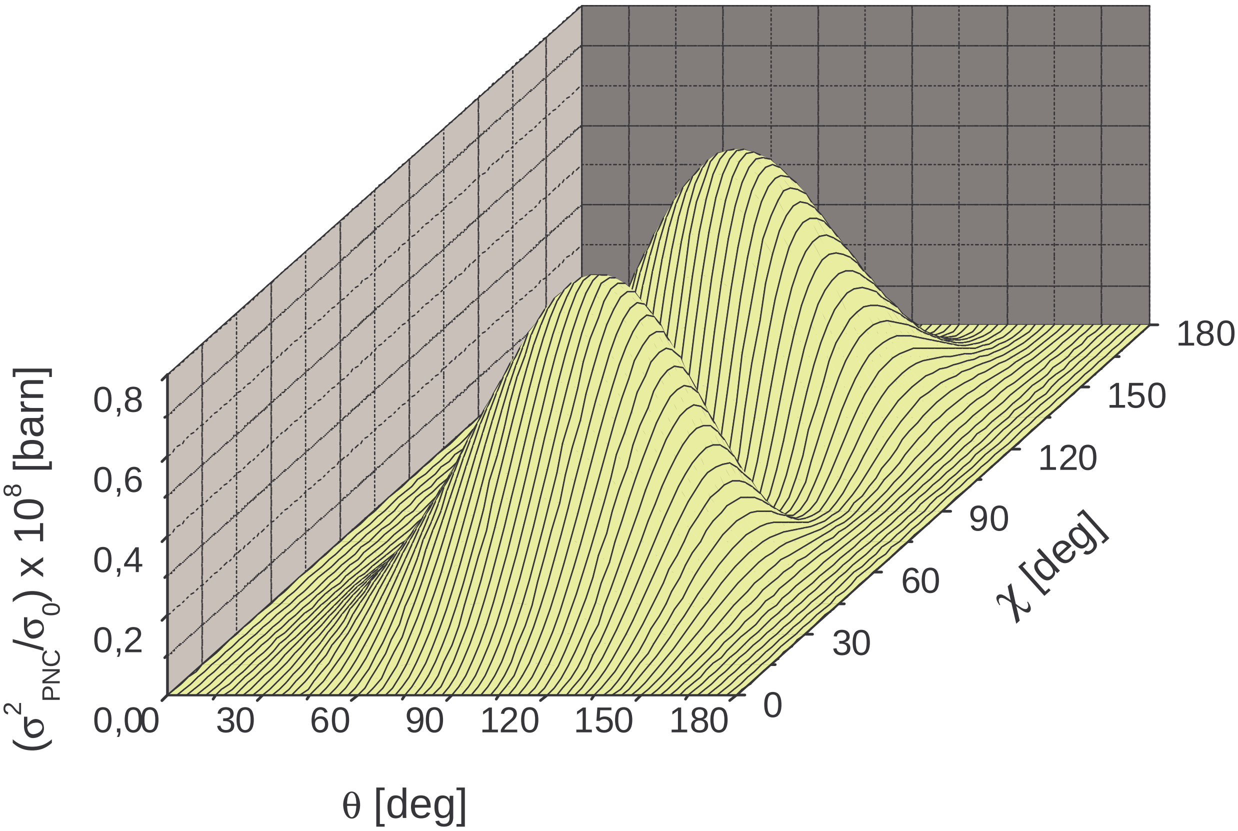


FIG. 5: The value $\sigma^2_{\mathrm{PNC}}/\sigma_0 \sim 1/L_0$ as a function of the inclination ($\theta$) and polarization ($\chi$) angles for the radiative recombination into the $2^3P_0$ state of He-like thorium at the incident electron energy of 1 eV. It is assumed that linearly polarized photons are detected in the experiment with unpolarized electrons and ions. The PNC contribution $\sigma_{\mathrm{PNC}}$ changes the sign under the replacement $\chi \to \pi - \chi$.

cm$^{-2}$s$^{-1}$, has been found at the angles $\theta = 92$ and $\chi = 76$ with $\sigma_0$=2429.3 barn and $\sigma_{\mathrm{PNC}}$ = 0.00038 barn. The maximum absolute value of the PNC contribution, reached at $\theta = 91$ and $\chi = 45$, amounts to $\sigma_{\mathrm{PNC}} = 0.00080$ barn with $\sigma_0$=19488 barn.

## IV. CONCLUSION

In this paper, we investigated the PNC effect on the cross section of the radiative recombination of an electron into the $2^1S_0$ and the $2^3P_0$ state of heavy He-like ions. The calculations were performed for the cases of thorium and gadolinium, where the PNC effect is strongly enhanced due to near degeneracy of the $2^1S_0$ and $2^3P_0$ states. Two scenarios of

possible experiments were studied. It was found that a promising situation occurs in the scenario, where linearly polarized photons are detected in experiment with unpolarized electrons and ions and the count rate difference between the two linear polarizations is measured simultaneously at different azimuth angles.

## V. ACKNOWLEDGMENTS

This work was supported by DFG (Grant No. 436RUS113/950/0-1), by RFBR (Grant No. 08-02-91967), and by GSI. The work of A.V.M., P.O.I, and V.M.S. is also supported by the Ministry of Education and Science of Russian Federation (Program for Development of Scientific Potential of High School, Grant No. 2.1.1/1136). V.M.S. acknowledges financial support by the Alexander von Humboldt Foundation. The work of A.V.M. was supported by the Dynasty foundation. G.P. acknowledges financial support by DFG.

TABLE I: The $2^3P_0$ - $2^1S_0$ energy difference in He-like ions near the crossing points [39, 40], in eV.

| Eu ($Z$=63) | Gd ($Z$=64) | Tb ($Z$ =65) | Dy ($Z$ =66) | Ac ($Z$ =89) | Th ($Z$ =90) | Pa ($Z$ =91) | U ($Z$ =92) |
|---|---|---|---|---|---|---|---|
| -0.249(69) | -0.023(74) | 0.29(12) | 0.462(84) | 1.52(40) | 0.44(40) | -0.43(50) | -2.81(8) |

TABLE II: Numerical results for the radiative recombination into the $2^1S_0$ and the $2^3P_0$ state of He-like thorium at the inclination angles $\theta$ corresponding to the minimum values of the luminosity $L_0$. The calculations are performed for the scenario, where the electron beam is fully polarized while the H-like ions are unpolarized and the photon polarization is not detected. $L_0$ is the luminosity defined by Eq. (18) at $T = 2$ weeks, $\sigma_0 = (\sigma_+ + \sigma_-)/2$ is the cross section without the PNC effect, and $\sigma_{\rm PNC} = (\sigma_+ - \sigma_-)/2$ is the PNC contribution.

| | RR into the $2^1S_0$ state | | | | RR into the $2^3P_0$ state | | | |
|---|---|---|---|---|---|---|---|---|
| $p_i^0$ [keV] | $\theta$ [grad] | $L_0$ [cm$^{-2}$s$^{-1}$] | $\sigma_0$ [barn] | $\sigma_{\rm PNC}$ [barn] | $\theta$ [grad] | $L_0$ [cm$^{-2}$s$^{-1}$] | $\sigma_0$ [barn] | $\sigma_{\rm PNC}$ [barn] |
| 0.001 | 180 | $9.1\times10^{26}$ | 4281.8 | 0.14 | 143 | $2.7\times10^{27}$ | 52856 | -0.28 |
| 0.005 | 0 | $4.5\times10^{27}$ | 530.59 | 0.022 | 142 | $1.3\times10^{28}$ | 10757 | -0.058 |
| 0.010 | 0 | $8.9\times10^{27}$ | 265.22 | 0.011 | 142 | $2.6\times10^{28}$ | 5346.7 | -0.029 |
| 0.050 | 0 | $4.3\times10^{28}$ | 52.963 | 0.0023 | 140 | $1.3\times10^{29}$ | 1096.3 | -0.0060 |
| 0.100 | 0 | $8.3\times10^{28}$ | 26.440 | 0.0011 | 139 | $2.4\times10^{29}$ | 551.34 | -0.0031 |
| 0.500 | 0 | $3.8\times10^{29}$ | 5.2346 | 0.00024 | 135 | $1.0\times10^{30}$ | 111.97 | -0.00067 |
| 1.000 | 0 | $7.0\times10^{29}$ | 2.5881 | 0.00012 | 131 | $1.9\times10^{30}$ | 57.751 | -0.00036 |
| 5.000 | 0 | $3.0\times10^{30}$ | 0.47948 | $2.6\times10^{-5}$ | 118 | $6.2\times10^{30}$ | 11.598 | $-8.8\times10^{-5}$ |
| 20.000 | 0 | $1.1\times10^{31}$ | 0.094911 | $6.0\times10^{-6}$ | 94 | $1.5\times10^{31}$ | 2.7367 | $-2.7\times10^{-5}$ |


[1] Khriplovich I B 1991 *Parity Nonconservation in Atomic Phenomena* (Gordon and Breach, London)

[2] Khriplovich I B 2004 *Phys. Scr. T* **112** 52

[3] Ginges J S M and Flambaum V V 2004 *Phys. Rep.* **397** 63

[4] Wood C S, Bennett S C, Cho D, Masterson B P, Roberts J L, Tanner C E and Wieman C E 1997 *Science* **275** 1759

TABLE III: Numerical results for the radiative recombination into the $2^1S_0$ state of He-like thorium at angles $\theta$ and $\chi$ corresponding to the minimum values of the luminosity $L_0$. The calculations are performed for the scenario, where the linearly polarized photons are detected in the experiment with unpolarized electrons and ions. $L_0$ is the luminosity defined by Eq. (18) at $T = 2$ weeks, $\sigma_0$ is the cross section without the PNC effect, and $\sigma_{\rm PNC}$ is the PNC contribution, which changes the sign under the replacement $\chi \to \pi - \chi$.

| $p_i^0$ [keV] | $\theta$ [grad] | $\chi$ [grad] | $L_0$ [cm$^{-2}$s$^{-1}$] | $\sigma_0$ [barn] | $\sigma_{\rm PNC}$ [barn] |
|---|---|---|---|---|---|
| 0.001 | 94 | 68 | $3.0\times10^{29}$ | 10858 | 0.012 |
| 0.005 | 94 | 68 | $1.5\times10^{30}$ | 2171.3 | 0.0024 |
| 0.010 | 93 | 68 | $3.0\times10^{30}$ | 1087.2 | 0.0012 |
| 0.050 | 92 | 68 | $1.5\times10^{31}$ | 217.57 | 0.00025 |
| 0.100 | 91 | 68 | $2.9\times10^{31}$ | 108.82 | 0.00012 |
| 0.500 | 87 | 68 | $1.5\times10^{32}$ | 21.706 | $2.5\times10^{-5}$ |


[5] Bennett S C and Wieman C E 1999 *Phys. Rev. Lett.* **82** 2484; **83** 889

[6] Derevianko A 2000 *Phys. Rev. Lett.* **85** 1618; 2001 *Phys. Rev. A* **65** 012106

[7] Kozlov M G, Porsev S G and Tupitsyn I I 2001 *Phys. Rev. Lett.* **86** 3260

[8] Sushkov O P 2001 *Phys. Rev. A* **63** 042504

[9] Johnson W R, Bednyakov I and Soff G 2001 *Phys. Rev. Lett.* **87** 233001

[10] Dzuba V A, Flambaum V V, Ginges J S M 2002 *Phys. Rev. D* **66** 076013

[11] Kuchiev M Y 2002 *J. Phys. B* **35** L503 ; Kuchiev M Y and Flambaum V V 2002 *Phys. Rev. Lett.* **89** 283002; 2003 *J. Phys. B* **36** R191; Flambaum V V and Ginges J S M 2005 *Phys. Rev. A* **72** 052115

[12] Milstein A I, Sushkov O P and Terekhov I S 2002 *Phys. Rev. Lett.* **89** 283003; 2003 *Phys. Rev. A* **67** 062103

[13] Sapirstein J, Pachucki K, Veitia A and Cheng K T 2003 *Phys. Rev. A* **67** 052110

[14] Shabaev V M, Pachucki K, Tupitsyn I I and Yerokhin V A 2005 *Phys. Rev. Lett.* **94** 213002; Shabaev V M, Tupitsyn I I, Pachucki K, Plunien G and Yerokhin V A 2005 *Phys. Rev. A* **72** 062105

[15] Porsev S G, Beloy K and Derevianko A 2009 *Phys. Rev. Lett.* **102** 181601

TABLE IV: Numerical results in case of the radiative recombination into the $2^3P_0$ state of He-like thorium at angles $\theta$ and $\chi$ corresponding to the minimum values of the luminosity $L_0$. The calculations are performed for the scenario, where the linearly polarized photons are detected in the experiment with unpolarized electrons and ions. $L_0$ is the luminosity defined by Eq. (18) at $T = 2$ weeks, $\sigma_0$ is the cross section without the PNC effect, and $\sigma_{\rm PNC}$ is the PNC contribution, which changes the sign under the replacement $\chi \to \pi - \chi$.

| $p_i^0$ [keV] | $\theta$ [grad] | $\chi$ [grad] | $L_0$ [cm$^{-2}$s$^{-1}$] | $\sigma_0$ [barn] | $\sigma_{\rm PNC}$ [barn] |
|---|---|---|---|---|---|
| 0.001 | 93 | 60 | $5.5\times10^{29}$ | 31208 | -0.015 |
| 0.005 | 92 | 60 | $2.8\times10^{30}$ | 6235.4 | -0.0031 |
| 0.010 | 92 | 60 | $5.5\times10^{30}$ | 3116.4 | -0.0015 |
| 0.050 | 91 | 60 | $2.7\times10^{31}$ | 621.76 | -0.00031 |
| 0.100 | 91 | 60 | $5.4\times10^{31}$ | 310.28 | -0.00015 |
| 0.500 | 88 | 60 | $2.6\times10^{32}$ | 61.426 | $-3.1\times10^{-5}$ |


[16] Gorshkov V G and Labzowsky L N 1974 *Zh. Eksp. Teor. Fiz. Pis'ma* **19** 768 [1974 *JETP Lett.* **19** 394 ]; 1975 *Zh. Eksp. Teor. Fiz.* **69** 1141 [1975 *Sov. Phys. JETP* **42** 581]

[17] von Oppen G 1991 *Z. Phys. D* **21** 181

[18] Schäfer A, Soff G, Indelicato P, Müller B and Greiner W 1989 *Phys. Rev. A* **40** 7362

[19] Karasiev V V, Labzowsky L N and Nefiodov A V 1992 *Phys. Lett. A* **172** 62

[20] Dunford R W 1996 *Phys. Rev. A* **54** 3820

[21] Labzowsky L N, Nefiodov A V, Plunien G, Soff G, Marrus R and Liesen D 2001 *Phys. Rev. A* **63** 054105

[22] Zolotarev M and Budker D 1997 *Phys. Rev. Lett.* **78** 4717

[23] Pindzola M S 1993 *Phys. Rev. A* **47** 4856

[24] Gribakin G F, Currel F J, Kozlov M G and Mikhailov A I 2005 *Phys. Rev. A* **72** 032109; arXiv:physics/0504129

[25] Eichler J and Meyerhof W 1995 *Relativistic Atomic Collisions* (San Diego, CA: Academic)

[26] Shabaev V M 2002 *Phys. Rep.* **356** 119

[27] Klasnikov A E, Artemyev A N, Beier T, Eichler J, Shabaev V M and Yerokhin V A 2002 *Phys. Rev. A* **66** 042711

TABLE V: Numerical results for the radiative recombination into the $2^1S_0$ and the $2^3P_0$ state of He-like thorium at angles $\theta$ and $\chi$ corresponding to the maximum absolute values of the PNC contribution $\sigma_{\rm PNC}$. The calculations are performed for the scenario, where the linearly polarized photons are detected in the experiment with unpolarized electrons and ions. The $\sigma_{\rm PNC}$ contribution changes the sign under the replacement $\chi \to \pi - \chi$.

| | | | RR into the $2^1S_0$ state | | RR into the $2^3P_0$ state | |
|---|---|---|---|---|---|---|
| $p_i^0$ [keV] | $\theta$ [grad] | $\chi$ [grad] | $\sigma_0$ [barn] | $\sigma_{\rm PNC}$ [barn] | $\sigma_0$ [barn] | $\sigma_{\rm PNC}$ [barn] |
| 0.001 | 93 | 45 | 34410 | 0.018 | 51554 | -0.018 |
| 0.005 | 93 | 45 | 6879.7 | 0.0035 | 10310 | -0.0035 |
| 0.010 | 92 | 45 | 3446.8 | 0.0018 | 5153.0 | -0.0018 |
| 0.050 | 92 | 45 | 688.69 | 0.00035 | 1030.1 | -0.00036 |
| 0.100 | 91 | 45 | 344.70 | 0.00018 | 514.60 | -0.00018 |
| 0.500 | 88 | 45 | 68.940 | 0.000036 | 102.30 | -0.000036 |

[28] Surzhykov A, Fritzsche S and Stöhlker Th 2002 *J. Phys. B* **35** 3713

[29] Fritzsche S, Indelicato P and Stöhlker Th 2005 *J. Phys. B: At. Mol. Phys.* **B38** S707

[30] Eichler J and Stöhlker Th 2007 *Phys. Rep.* **439** 1

[31] Maiorova A V, Surzhykov A, Tashenov S, Shabaev V M, Fritzsche S, Plunien G and Stöhlker Th 2009 *J. Phys. B: At. Mol. Opt. Phys.* **42** 125003

[32] Yerokhin V A, Shabaev V M, Beier T and Eichler J 2000 *Phys. Rev. A* **62** 042712

[33] Surzhykov A, Jentschura U D, Stöhlker Th and Fritzsche S 2008 *Eur. Phys. J. D* **46** 27

[34] Shabaev V M, Yerokhin V A, Beier T and Eichler J 2000 *Phys. Rev. A* **61** 052112

[35] Rose M E 1957 *Elementary Theory of Angular Momentum* (New York: Wiley)

[36] Salvat F, Fernandez-Varea J M and Williamson Jr W 1995 *Comput. Phys. Commun.* **90** 151

[37] Stöhlker Th, Banas D, Beyer H F, Gumberidze A, Kozhuharov C, Kanter E, Krings T, Lewoczko W, Ma X, Protic D, Sierpowski D, Spillmann U, Tachenov S and Warczak A 2003 *Nucl. Instr. and Meth. in Phys. Res. B* **205** 210

[38] Tachenov S, Stöhlker Th, Banas D, Beckert K, Beller P, Beyer H F, Bosch F, Fritzsche S, Gumberidze A, Hagmann S, Kozhuharov C, Krings T, Liesen D, Nolden F, Protic D, Sierpowski D, Spillmann U, Steck M and Surzhykov A 2006 *Phys. Rev. Lett.* **97** 223202

[39] Artemyev A N, Shabaev V M, Yerokhin V A, Plunien G and Soff G 2005 *Phys. Rev. A* **71** 062104

[40] Kozhedub Y S and Shabaev V M unpublished.

[41] Kozhedub Y S, Andreev O V, Shabaev V M, Tupitsyn I I, Brandau C, Kozhuharov C, Plunien G and Stöhlker Th 2008 *Phys. Rev. A* **77** 032501

[42] Yerokhin V A, Indelicato P and Shabaev V M, 2006 *Phys. Rev. Lett.* **97** 253004

[43] Brandau C, Kozhuharov C, Harman Z, Müller A, Schippers S, Kozhedub Y S, Bernhardt D, Böhm S, Jacobi J, Schmidt E W, Mokler P H, Bosch F, Kluge H-J, Stöhlker Th, Beckert K, Beller P, Nolden F, Steck M, Gumberidze A, Reuschl R, Spillmann U, Currell F J, Tupitsyn I I, Shabaev V M, Jentschura U D, Keitel C H, Wolf A and Stachura Z 2008 *Phys. Rev. Lett.* **100** 073201